# THE VIOLENT VS. THE SILENT ASPECTS OF VORTEX RING STATE AND THE PARTICULAR CASE OF THE DOUBLE-SWEPT H160 BLADE

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**Abstract**

In this study numerical simulations are used to examine the rotor wake effects on the lift generation of a generic main rotor in low-speed descending flight. The VRS envelope is mapped for three different disc loadings, and the reduction using the hover induced velocity is demonstrated. From an operational standpoint, it is important to explain how pilots may involuntarily develop high sink rates during final approach. Therefore, besides the known dynamic part of the VRS phenomenon, such as thrust and moments fluctuations, we focus on the quasi-static drop of lift with increasing rate of descent, and the associated loss of rotor heave damping. It is shown that the loss, or even inversion, of the rotor heave damping is dependent on disc loading, and lightly loaded helicopters are more prone to develop unexpected rates of descent, even though the dimensionless VRS boundaries are fairly the same for all disc loadings. The effectiveness of raising the collective to arrest the descent rate, depending on the severity of VRS, is also shown. This part is related to an open debate as to whether the pilot should raise or lower the collective inside VRS. Finally, the H160 rotor with its double-swept blades is compared to the generic rotor with straight blades in the same flight regime. It is found that thanks to a strong link between rate of descent and blade elastic twist the H160 rotor shows a much better behavior in heave damping and less thrust fluctuations than the generic rotor.

## 1. NOTATIONS

Symbols

| | |
|---|---|
| $R$ | Rotor radius, m |
| $v_{io}$ | Theoretical induced velocity in HOGE, m/s |
| $\beta_{1c}$ | Longitudinal blade flapping (1st harmonic) |
| $\beta_{1s}$ | Lateral blade flapping (1st harmonic) |
| $\rho$ | Air density |
| $\omega$ | Rotor angular velocity, rad/s |

Acronyms:

| | |
|---|---|
| AH | Airbus Helicopters |
| b | Number of blades |
| CFD | Computational Fluid Dynamics |
| DL | Disc loading (N/m²) |
| DT0 | Collective pitch, in deg |
| DTC | Lateral cyclic, in deg |
| DTS | Longitudinal cyclic, in deg |
| FAA | Federal Aviation Administration, USA |
| FW | Free Wake (code) |
| FZG | Rotor thrust, in daN |
| HOGE | Hover out of ground effect |
| LES/DES | Large/Detached Eddy Simulation |
| MXG | Lateral moment on rotor center, in daN·m |
| MYG | Longitudinal moment on rotor center, in daN·m |
| ONERA | French aerospace research institute |
| VM | Vortex Methods |
| VRS | Vortex Ring State |
| Vx | Horizontal component of the velocity seen by the rotor disc (parallel to the disc), in kts |
| Vz | Vertical component of the velocity seen by the rotor disc (perpendicular to the disc), in fpm. Here Vz is positive when descending (rate of descent). |

## 2. INTRODUCTION

The Vortex Ring State (VRS) is a dangerous aerodynamic phenomenon that occurs at low speed and vertical descending flight. Under these conditions the turbulent wake of the rotor is not sufficiently convected away, instead it returns in the vicinity of the rotor disc and forms large recirculating unsteady vortical structures. The result is excessive thrust fluctuations, reduction of control authority, and even partial loss of generated lift. This situation, combined with increased pilot workload, can become a significant contributing factor to accidents.

Since the early 1950's the phenomenon was already known and documented [Ref 1. & 2.]. Throughout the past decades, and all around the world, extensive research has been dedicated to the topic, using all the available means: wind tunnel tests, flight tests, and recently, numerical simulations [Ref. 3 – 8]. However, despite a huge volume of valuable research, we observe today that the primary and most important end-customer of this effort, the helicopter pilot, is faced with multiple and somehow contradictory instructions from various sources about how to deal with this phenomenon. For example, some sources instruct to raise the collective lever [Ref. 9], while in VRS conditions, whereas other sources ask for the opposite [Ref. 10]. Some sources suggest pushing the cyclic forward to gain speed, while others (and not without reason) propose lateral cyclic. The lack of global consensus is a clear indicator that we, as H/C community, have not yet understood the full extent of VRS-induced rotor behavior, and how to convert the specific scientific knowledge into a clear and simple message to the people flying these machines.

The purpose of this work is to revisit the basics of VRS, using simple numerical tools (vortex methods), and extend to as many as possible parametric studies, in order to understand and perhaps quantify the dynamic (violent) and quasi-static (silent) aspects of VRS. One finding amongst others was that not all rotors are the same with respect to VRS, thus the particular case of the H160 rotor is also shortly presented.

## 3. METHOD

### 3.1. Numerical tools

Vortex methods (VM) for helicopter rotors, such as the free wake (FW) codes used in this study, have been developed around the 1980's, aiming primarily at blade loads computations. Their complete resolution and conservation of the wake combined with fast computation make them ideal for this type of investigations, allowing large parametric studies. Although the physical modelling is not as refined as in "full-CFD" codes (URANS, LES/DES), in-house (AH) experience of using VM for low speeds interactions studies in the past decade allows for a good level of confidence in the results.

The tools used in this study are created at ONERA, and have numerous applications in AH aerodynamics investigations. The first code [Ref. 11 & 12] is HOST-MINT using a strong coupling between the FW solver (MINT) and the aeromechanics tool (HOST) that allows for re-trimming the rotor during the simulation as the flow surrounding the rotor is changing (i.e., flow recirculation in VRS conditions). The evolution of control inputs during the simulation gives us a good idea of the pilot workload. At the same time HOST can be used with soft blades (elastic deformations allowed), thus the blade elasticity, mainly in the flapping and torsion axes, can also be taken into account. This might not be so important for typical straight blades, but as we will see later in this paper it is essential for double-swept blades (H160 rotor).

On the other hand, the PUMA [Ref. 13] code is standalone (no coupling with HOST), so the control inputs are prescribed, the blades are rigid, and flapping/lagging angles are also prescribed and constant. The great advantage over the HOST-MINT code, is that PUMA is substantially faster, and allows for flow visualization: instantaneous slices, videos, and averaged flow field. It also allows for transient computations where a prescribed control input is varying during the simulation (i.e. collective input inside VRS).

### 3.2. Procedure

Besides some preparatory sensitivity analyses on solver options, most computations were conducted using a 6° azimuthal step (60 steps per rev), a wake age of 8 revs, and a duration of 56 revs. The blade is modeled using 20 radial stations for wake panels emission and section loads. Finer azimuthal step, denser radial stations, and greater wake age, do not add significantly to the quality of the results. They only add unnecessary wall time (physical duration of each simulation).

For the generation of VRS mappings at different disc loadings (DL), and different rotors, cross-sweeps between forward velocity and flight path angle have been performed. In total approx. 100 points (Vx-Vz combination) were computed for each map, and Kriging interpolation has been used in between them (example in Figure 1).

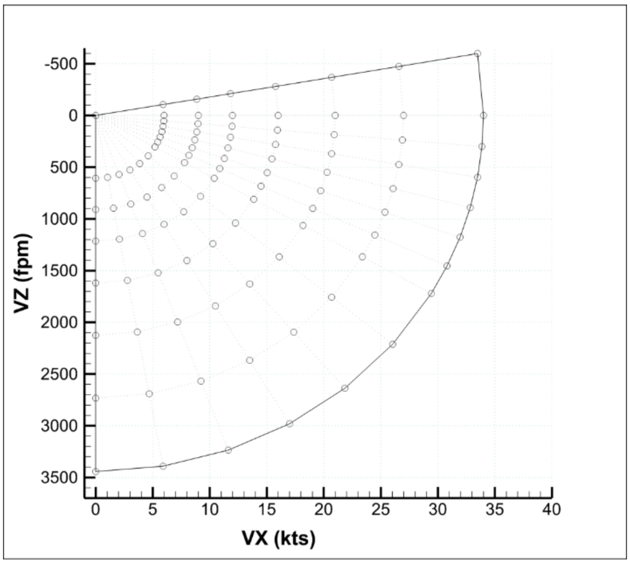


**Figure 1**: computation points for each VRS mapping

The trim law of each computation point (using HOST-MINT) was a target thrust and zero flapping ($\beta_{1c}$=$\beta_{1s}$=0°). The three commands (collective and longitudinal/lateral cyclic) are free to evolve until an *almost converged* solution is reached. We use the ambiguous term "almost converged" because inside VRS there is no fully converged solution, and this is a natural consequence of the unsteadiness and the stochastic character of the inflow. In Figure 2 we present an example of the generic rotor with 6.2 tons target thrust, at 2100 fpm of vertical descent (inside VRS). The thrust/moments fluctuations are visible, along with the evolution of the three commands with time. At 12 seconds the computation stops, as we assume that the simulation is lengthy enough to provide us with useful data.

In the example of Figure 2 we can observe that thrust fluctuations are mainly composed by a slow frequency and large amplitude content (here, approx. ±1000 daN around the target thrust of 6200 daN), which is the result of inflow fluctuations due to VRS. We can also see a high frequency and small amplitude content (±200 daN), which corresponds to b/rev vibratory loads on the blades. It is interesting to see (Figure 3) that in the frequency spectrum of the thrust fluctuations most of the content is concentrated below 3Hz, and pick content is around 0.5-1Hz, which is also in the range of piloting frequencies. This is another reason why VRS interferes with pilot actions and causes additional difficulty to exit this condition.

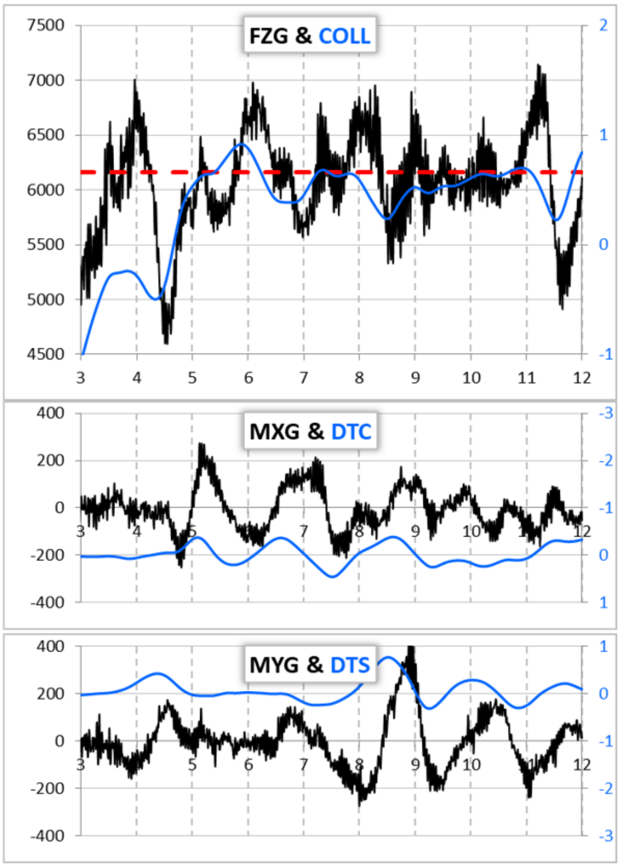


**Figure 2**: time evolution of thrust/moments (left hand axis, forces in daN, moments in daN·m) for the generic rotor at 6.2 tons of target thrust (red dashed line), and 2100 fpm of vertical descent, and the three commands (right hand axis, in blue, in deg).

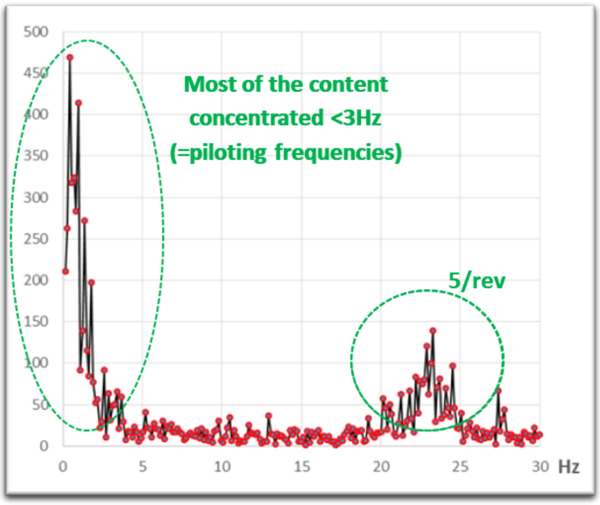


**Figure 3**: thrust fluctuations (of the example in Figure 2) represented here in the frequency domain.

As it will be shown later in this paper, the disc loading (DL) plays an important role in VRS mapping and rotor behavior. In this study we tried to cover various disc loadings, representing from heavy to very light helicopters. Light helicopters have a DL between 10 and 20 kg/m² (~daN/m²), while heavy helicopters can have a minimum operational DL (empty weight + 20% of payload capacity) of more than 40 kg/m² (Figure 4). In Table 1 we present the test cases that have been explored during this study.

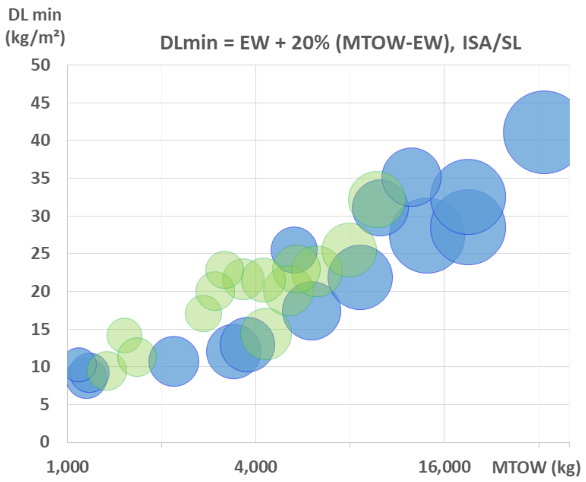


**Figure 4**: Evolution of disc loading (DL) with maximum take-off weight for two major US helicopter manufacturers. The diameter of each bubble depicts the diameter of the main rotor.

**Table 1**: Test cases of this study

| Rotor | Condition | Disc loading (daN/m²/σ) |
|---|---|---|
| Generic | ISA/SL | ~36 |
| Generic | 9500ft/ISA+20 | ~65 |
| Generic | ISA/SL | 25 |
| Generic | ISA/SL | 15 |
| H160 | ISA/SL | 39 |
| H160 w/ rigid blades | ISA/SL | 39 |

## 4. RESULTS & DISCUSSION

### 4.1. The violent aspects of VRS

The violent reaction of a helicopter inside VRS conditions, besides increased vibrations and probably rotor noise, is due to the large and chaotic fluctuations of the inflow on the rotor blades. The famous "donut shape" recirculation in the periphery of the rotor disc is very unsteady, causing significant oscillations in thrust (lift) and moments around the rotor head center. Additionally, this inflow unsteadiness can impact the tail rotor, causing oscillations in the yaw axis.

In the literature, one can find several metrics aiming at quantifying the severity of these oscillations, usually a percentage of thrust oscillations around the mean. In this study the simple metrics that we will use is only the sum of the low frequency content, ignoring the contribution of the b/rev vibratory loads (seen) the example of Figures 2 and 3). We then define the low frequency oscillatory load (FZ in the graphs) as:

$$\mathrm{FZ} = \sum_{i=0}^{3Hz} A_{Fz_i}$$

Then if we plot the FZ on a typical Vx-Vz graph (VRS mapping) for the case of the generic rotor with straight blades at 36 daN/m² of disc loading we obtain (Figure 5):

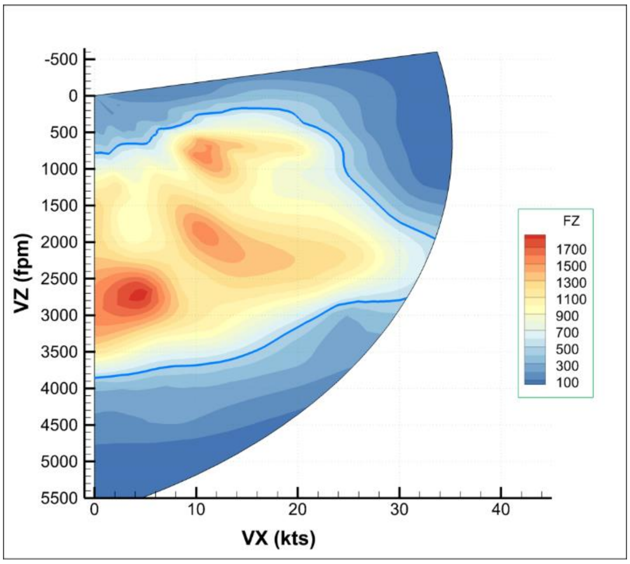


**Figure 5**: distribution of low frequency oscillatory thrust (FZ) in the low speeds descending flight domain. Red colored areas represent high oscillations. The blue line corresponds to iso-FZ=500 that we will use as a threshold of significant thrust oscillations. Disc loading: 36 daN/m²

Comparing the blue (small oscillations) against the yellow/orange areas (large oscillations), we see that significant thrust oscillations can occur as early as 20-25 kts of horizontal speed, or 500 fpm of rate of descent. This might not be fully developed VRS, but more generally the wake of the rotor interacting with the blades, and could potentially serve to provide the signs of approaching a dangerous situation. Of course, this is the result of a numerical simulation, and absolute values are not to be trusted completely. Nevertheless, we can arbitrarily define a threshold of FZ=500, above which we consider the thrust oscillations as significant. The same type of mapping is computed also for disc loadings of 25 and 65 daN/m², and shown in the following figures (Figures 6 & 7).

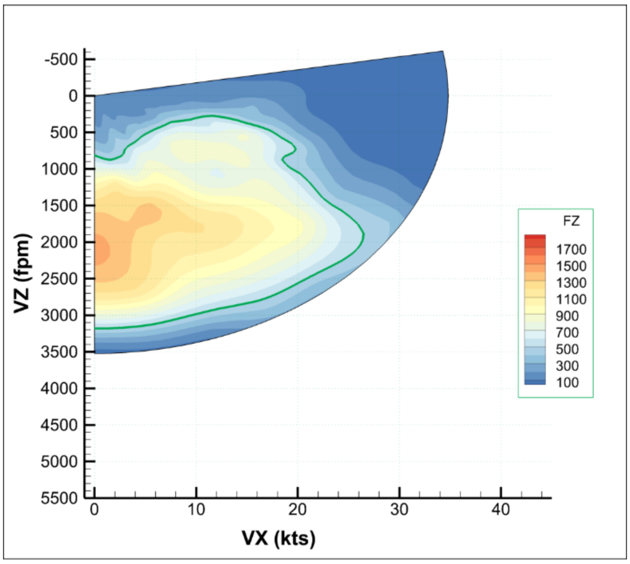


**Figure 6**: distribution of low frequency oscillatory thrust (FZ). Red colored areas represent high oscillations. The green line corresponds to iso-FZ=500. Disc loading: 25 daN/m²

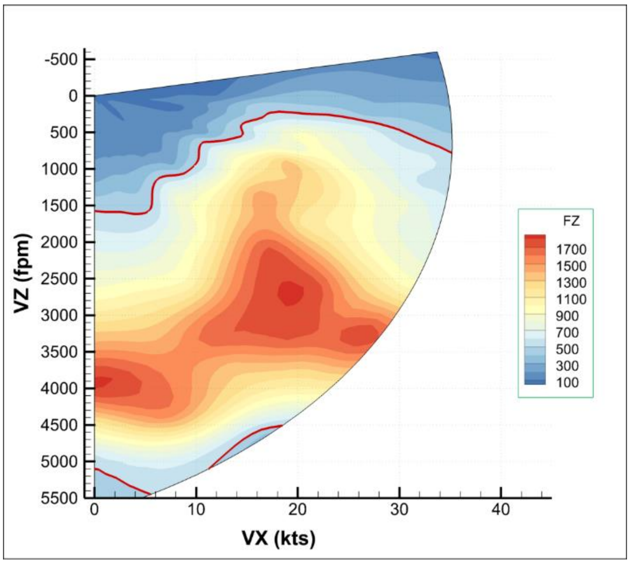


**Figure 7**: distribution of low frequency oscillatory thrust (FZ). Red colored areas represent high oscillations. The red line corresponds to iso-FZ=500. Disc loading: 65 daN/m²

We observe that for the lightly loaded rotor (DL=25 daN/m²) the area on the Vx-Vz graph of oscillating thrust is reduced in size, compared to DL=36, while for the high DL of 65 daN/m² the area is much greater. We also observe that the intensity of the oscillating thrust increases with DL, and the peak points of this intensity (orange/red pockets) are not at the same speeds (Vx or Vz). This means that the overall behavior of a helicopter inside the VRS domain depends greatly on its disc loading.

As it is found often in the literature, the VRS mapping can be reduced by the average theoretical induced velocity in hover ($v_{io}$):

$$v_{io} = \sqrt{\frac{DL}{2\rho}}$$

If we choose to reduce the corresponding Vx and Vz of the iso-FZ=500 line for each of the three DL (Figures 5, 6, 7), we observe (Figure 8) that the three different limits of the VRS mapping are almost identical. This means that the thrust oscillations related to VRS, or near-VRS, conditions become significant roughly at the same combinations of horizontal speed (Vx) and rate of descent (Vz) when these two are reduced by $v_{io}$.

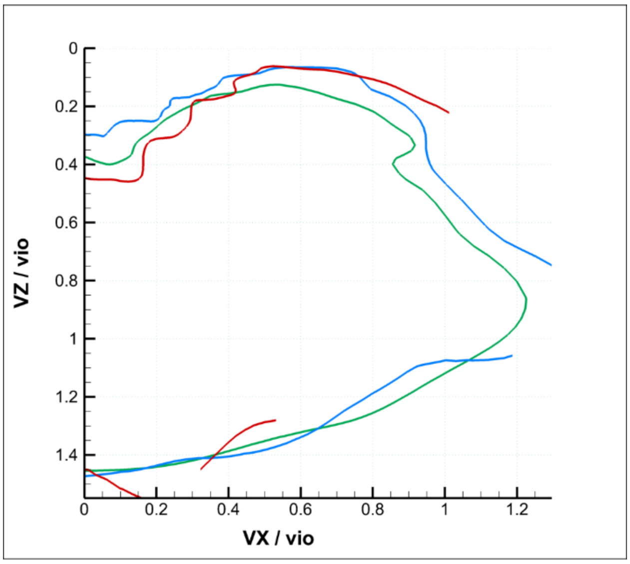


**Figure 8**: superposition of the three iso-FZ=500 of oscillatory thrust content for the different disc loadings as shown previously.

This does not mean that VRS will appear at, for example, Vz/vio=0.2 and Vx/vio=0.6, but most probably thrust oscillations will be experienced by the flight crew. If these oscillations are significant enough, they might provide the warning sign about approaching real VRS conditions. Low frequency thrust oscillations can be modeled and used in Flight Simulators, in order to provide a more physical modelling for pilots training.

### 4.2. The silent aspects of VRS

Besides the significant oscillations in thrust and moments inside the VRS domain (the violent aspects), which add difficulty to control the helicopter, a different expression of the VRS phenomenon can be considered as even more dangerous. Under the title "the silent aspects of VRS" we imply the loss and even inversion of the damping in the vertical (heaving) axis normally provided by the main rotor, which is linked to the loss of average lift (thrust) when entering VRS. This might be the main reason why pilots, despite their training and experience, still enter inadvertently in the VRS domain, especially in vertical or near-vertical descent.

A simplified drawing of the main rotor thrust dependence on vertical speed (Vz or rate of descent) tries to give some basic explanations (Figure 9): for a given/fixed collective pitch angle, when the rate of descent increases, a component of vertical airspeed crosses the rotor disc and increases the airfoils incidence, and thus the total lift of the rotor. This means that the rotor provides positive damping in the vertical axis. In fact, for a given set of H/C weight and atmospheric conditions, a collective pitch corresponds to a unique value of Vz.

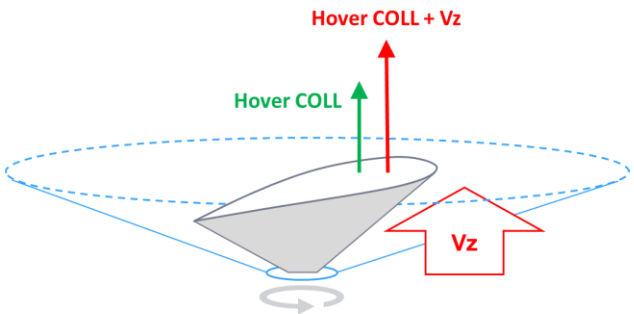


**Figure 9**: depiction of a simplified (one bladed) main rotor thrust vector at fixed collective under the influence of rate of descent. When the rate of descent increases then the lift also increases, providing positive damping.

At the same time the main rotor acts as a direct and linear controller of the vertical speed through the collective pitch: a continuous, monotonous and quasi-linear relation between collective pitch and Vz values (Figure 10). The combination of vertical damping and direct control gives the pilot the ability to safely and easily control the vertical axis. Unfortunately, this behavior applies only outside the quasi-vertical VRS domain. As we observe in Figure 10, simulations that include VRS modeling converge to an increasing value of collective pitch with increasing rate of descent (in this case, in the range of 900 to 1600 fpm). This means that we have negative damping, and explains why without any action from the pilot (on collective) the rotor and the helicopter as a whole "is sinking" in an accelerating manner to higher rates of descent (Vz). When the high Vz are established then the "violent aspects of VRS" shake the H/C and complexify even further the piloting.

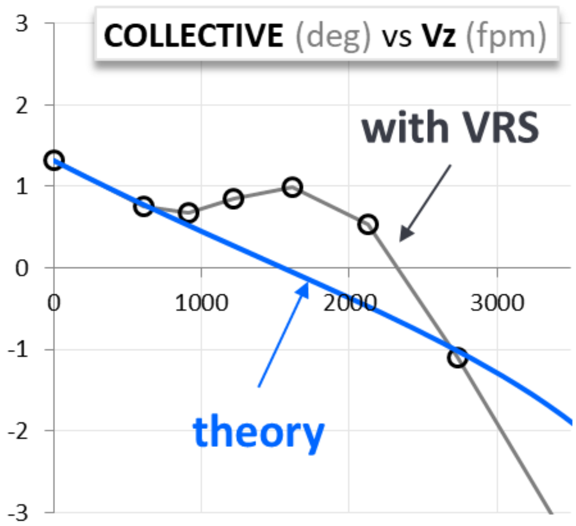


**Figure 10**: evolution of required collective to sustain 1g flight with rate of descent (Vz) for two types of simulation: one theoretical (blue line), and one with activated VRS modeling (free wake, black line). Between 1000 and 2000 fpm the required collective increases (compared to theory) because of the loss of lift inside VRS.

The increased collective pitch requirement (compared to theory without VRS) in VRS conditions means loss of average lift. Often in the literature we find sources that explain this loss of lift through the blade airfoils stalling, especially on the inboard stations of the blade. It is true that at high rates of descent (VRS or not) part of the flow crosses the rotor disc around the center (absence of airfoils <25%R). It is called "the fountain effect". Also because of low local peripheral speed (U=ωr) of the inboard stations of the blade (r/R<40%), the generated lift is small, and the associated inflow is weak. In VRS conditions “the fountain effect” and the weak inflow of the inboard stations, combined with the strong flow coming from below (Vz), may lead to some inboard stations experiencing locally high angles of attack, and possibly stall.

However, these stations’ contribution to the total lift (and torque) of the rotor is small to almost insignificant. Thus, whether these stations stall or not it is not important. In a typical (vortex method) hover simulation of a generic rotor (Figure 11) we see that only a meager 5% of the total lift is produced in the first 40% of the blade radius (inboard stations), while the last 20% of the blade radius (close to tip) produces 50% of the total lift. It is evident that if we are to look where the lift loss occurs in VRS, we have to focus on the blade area close to the tip.

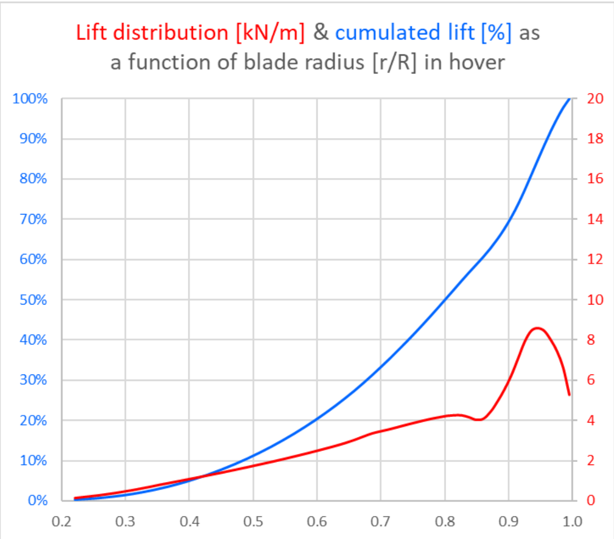


**Figure 11**: lift distribution in kN/m (red line, right axis) and cumulated lift in % (blue line, left axis) in a typical hover simulation. Most of the lift is generated in the last 20% of the blade radius, close to the tip. The contribution of the first 40% of the blade (inboard stations) is insignificant.

Indeed, when we plot the radial distribution of inflow (airflow crossing the rotor disc) for three critical rates of descent of Figure 10 (900, 1200, 1600 fpm) where the collective pitch vs. Vz slope is positive (meaning negative damping and loss of lift), we observe that the inflow increases with rate of descent in the outboard stations of the blade (close to the tip, see Figure 12).

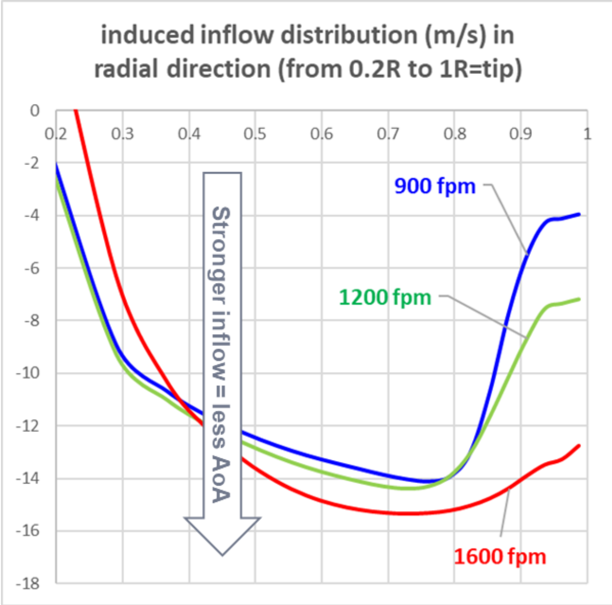


**Figure 12**: inflow radial distribution for three rates of vertical descent (Vz). We see that for this disc loading, in the range of Vz from 900 to 1600 fpm, as Vz increases the inflow close to the tip of the blade (>80%R) also increases. This reduces airfoils lift.

Under these conditions the airfoils close to the tip (say, >80%R) see more inflow, meaning more air coming from above, so for the same geometric incidence (pitch) the aerodynamic incidence (angle of attack) diminishes, and lift is simply reduced. This is the main explanation as to why the rotor with increasing rate of descend produces less lift (instead of the opposite according to theory without VRS).

Another interesting aspect of the loss of lift inside VRS is the dependence on disc loading. The example of Figure 10 corresponds to DL=36 daN/m². When we plot the same simulations of vertical descents for different disc loadings, we obtain something that was previously unknown. In Figure 13 we plot the required collective differential (Δ from hover value) for constant average lift, as a function of rate of descent, for DL ranging from 15 to 65 daN/m². We observe that while for 36 daN/m² (of DL) there is only a slight increase in required collective between 900 and 1600fpm, for lighter disc loadings (15 and 25 da/m²) the increase of required collective is much stronger and very sharp. Especially for 15 daN/m² the equivalent loss of lift (if collective was to be held constant) is roughly 0.2g (20% of total lift), and it takes place in only 300 fpm of difference in Vz. More importantly the required collective at 1200 fpm clearly exceeds the hover value. This means that if the collective is not properly set for hover and, for any reason, the rate of descent is allowed to "slide" at around 900 fpm (again, these are values coming from a simulation code), the H/C will drop suddenly inside VRS and higher Vz will develop. On the other hand, we also observe that for very high disc loadings, the VRS does not manifest itself as a loss of lift, but only as thrust/moments oscillations as mentioned earlier. Perhaps the rotor downwash is so strong in this case, that the peripheral recirculation of the flow around the tips (that causes the reduction of local AoA) is kept clear outside the rotor radius.

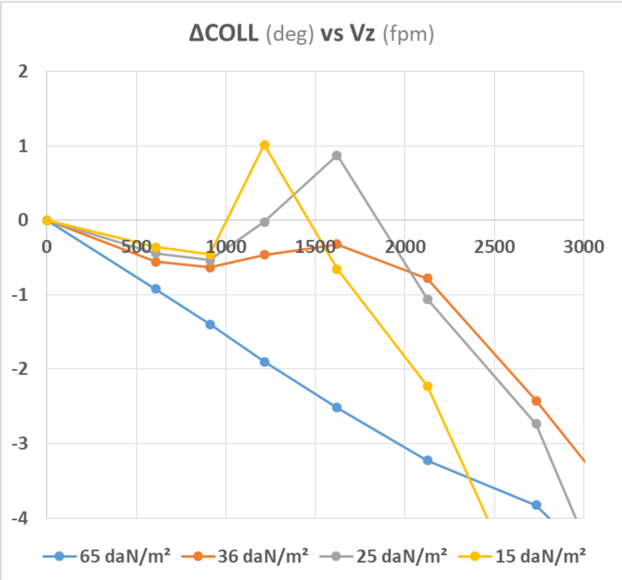


**Figure 13**: required collective (Δ from hover value) as a function of vertical descent rate, for four different disc loadings.

The sudden increase in required collective (=loss of lift) for lighter disc loadings, does not only occur in vertical descent. If we plot the necessary collective for the complete cartography of a VRS mapping (Vx/Vz chart), and superpose areas where the collective-to-Vz gradient is positive (meaning loss of lift), we observe (Figure 14, DL=25 daN/m²) that in vertical descent (Vx=0) the loss of lift occurs mainly between 800 and 1600 fpm, but with some small forward (or rear/sideward) speed, loss of lift can be encountered even at 500 fpm. Again, it should be reminded that this is a product of numerical simulation and all these results should be validated with more sophisticated tools and of course flight tests.

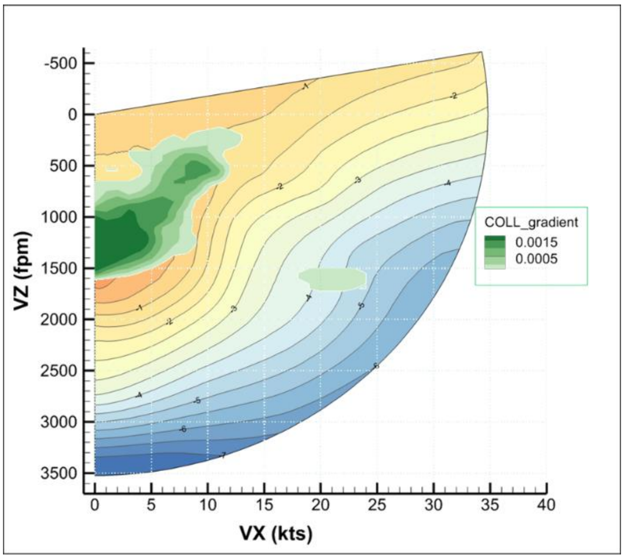


**Figure 14**: required collective for constant average disc loading of 25 daN/m² (orange=more / blue=less), and areas (green) where the collective-to-Vz gradient becomes positive, meaning loss of lift due to VRS.

### 4.3. Transient simulations on collective effectiveness inside VRS

All of the above simulations (sections 4.1 and 4.2) are considered "steady", meaning that Vx/Vz are fixed in a wind tunnel-like configuration, and the controller operates the commands (collective, cyclic) aiming at maintaining a constant average disc loading target. In order to simulate real pilots' reactions when they find themselves inside VRS, transient simulations have been also conducted, where "ramps" of gradual collective increase were tested.

The motivation behind these studies, and transient simulations in particular, comes from a global open debate on what pilot action on collective is the most appropriate in order to safely exit VRS without excessive loss of height. Airbus Helicopters (AH) published recently the Safety Information Notice (SIN-3123, Ref. 10) where it is stated that when VRS is detected collective pitch should be raised, if residual power is available. This instruction does not come of course only from simulations, but from several flight test campaigns as well. However, on the completely opposite side, one can find in FAA's "Helicopter Flying Handbook" Chapter 11 (Ref. 9) the information that raising the collective only increases the sink rate, and the lowering the collective is necessary to exit VRS conditions. At least both entities agree that immediate forward cyclic is vital to gain some forward speed and exit VRS. On top of this fundamental disagreement on collective (raising or lowering), we also have the recent "Vuichard maneuver" (from Swiss pilot/instructor C. Vuichard), that quickly gained publicity from video sharing platforms on the internet, and for many it has been embraced as the new miracle anti-VRS solution. One has to understand that for a very dangerous phenomenon like VRS, pilots around the world cannot be trained with conflicting instructions. In very stressful and life-threatening situation like VRS with small vertical separation from the ground, a pilot does not have time to think whether he or she should raise or lower the collective. The reaction must be "pre-registered", automatic, and immediate.

In order to investigate the collective effectiveness inside VRS some additional simulations have been conducted by ex-intern Antoine Outil (now an Air France cadet pilot) under the supervision of the author. In the following two graphs (Figures 15 and 16) collective inputs of +1°/sec are applied for two cases of vertical descent: 1600 fpm ("incipient" VRS) and 2100 fpm ("deep" VRS). For each simulation the +0° collective represents the reference computation, and two inputs are also shown: +0.5° above the reference that corresponds to a mild collective input with minimal impact on available power margins, and +2° that is a strong collective input with the associated power consumption.

We observe (Figure 15) that for the 1600 fpm case (of course, depending on DL and other factors), with small thrust oscillations in general, even the mild +0.5° collective input creates a clear increase in lift. One has to know that for this rotor, which corresponds to an 6-8 tons H/C, 1° of collective corresponds approx. to an additional 1 ton of lift. However, at 2100 fpm (Figure 16), where the thrust oscillations are very large, the mild +0.5° input has no effect on additional lift generation whatsoever. Even for the strong input of +2° (assumption: power is available for such input) it is hard to distinguish a clear increase in average lift, especially for the first few seconds after the input. At least we don't observe any decrease in lift either. These results can be translated in real life situations as: (a) on early signs of VRS, if successfully detected, applying positive collective can be a very efficient strategy, and (b) when well inside VRS it is very probable that a positive collective input will be almost completely inefficient, but at least not detrimental (i.e., leading to further loss of lift as stated in some source in the literature).

It is worth mentioning that these results, although generated by a simple tool, have been compared with similar studies carried out at AH/Germany (Ref. 14) and with a dedicated flight tests campaign. The general trend is the same: applying positive collective in "incipient" VRS is clearly effective, and in "deep" VRS it is generally ineffective. However, increased collective will provide immediate lift once the helicopter has translated out of the Vortex Ring during a recovery maneuver, which will minimize the loss of altitude.

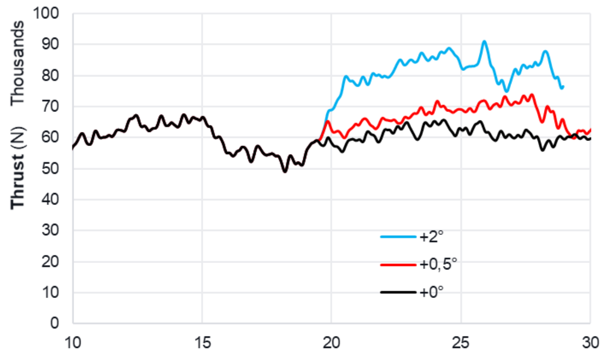


**Figure 15**: evolution (time in sec) of rotor lift for three different cases of collective input at 1600 fpm of vertical descent: (a) no input (black), (b) mild input (red), (c) strong input (cyan)

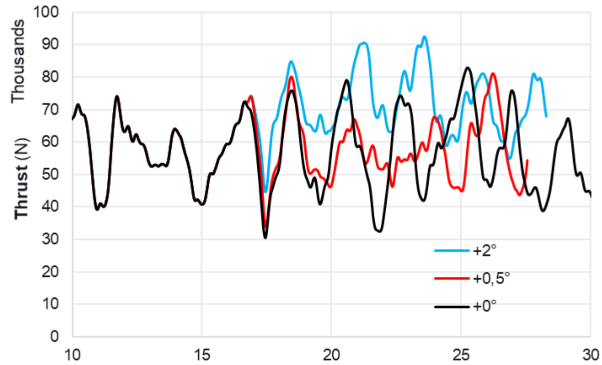


**Figure 16**: evolution (time in sec) of rotor lift for three different cases of collective input at 2100 fpm of vertical descent: (a) no input (black), (b) mild input (red), (c) strong input (cyan)

### 4.4. The particular case of the H160 rotor

The H160 rotor is equipped with Blue Edge blades (Figure 17), whose main distinctive characteristic is the double sweep in the outboard part of the blade. In fact, about the last 10% of blade radius sets the quarter chord line behind the feathering axis. This creates a specific aeroelastic behavior: when the blade tip area is loaded, a negative torsion moment will be created, and this results in over-twisting the blade and effectively reducing the pitch angle of the airfoils, especially close to the tip. The opposite happens of course when the blade tip area is unloaded: the blade becomes less twisted.

**Figure 17**: the distinctive double swept shape of the Blue Edge blade equipping the H160 rotor.

As discussed in the previous section of this paper, the loss of average lift when entering VRS is caused by the increased inflow close to the tip, due to the large recirculation of the flow, resulting in reduction of local airfoils angles of attack, and finally local lift. When we combine this physical mechanism with the specific aeroelastic behavior of the H160 blade, it is easy to understand that when the tip inflow increases and angles of attack decrease, the tip becomes unloaded, and the whole blade becomes less twisted. This is the equivalent of adding more collective, without any pilot action.

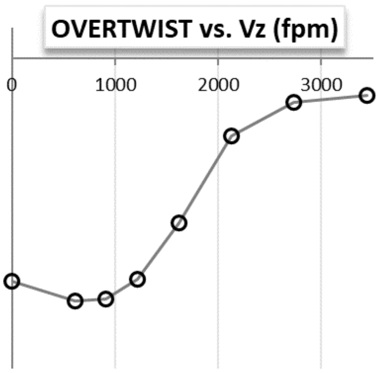


**Figure 18**: evolution of H160 blade over-twist (more negative than neutral geometric twist) with vertical rate of descent, at 39 daN/m² of disc loading.

As we observe in Figure 18 (tip over-twist in degrees as a function of vertical descent rate or Vz), starting from hover with a few degrees of over-twist (more negative blade twist), as the rate of descend increases and reaches about 600 to 800 fpm (for this disc loading of 39 daN/m²), the blade tip area will encounter the first signs of local lift loss, and the whole blade will start under-twisting, as if the pilot was adding collective pitch.

The effect on the evolution of the actual collective pitch with rate of descent (Figure 19), is that in order to keep a constant disc loading (corresponding to the aircraft weight), the required collective on a H160 has a clear monotonous negative slope in below 800 fpm, meaning that lift loss cannot occur inadvertently, and that the rotor on its own has a positive damping on the vertical axis. This natural behavior of the H160 blades ultimately protects the pilots from accidentally encountering a low-G condition and sinking further into VRS. The required collective pitch evolution is directly compared with the one of a generic straight blade that we saw previously in Figure 10.

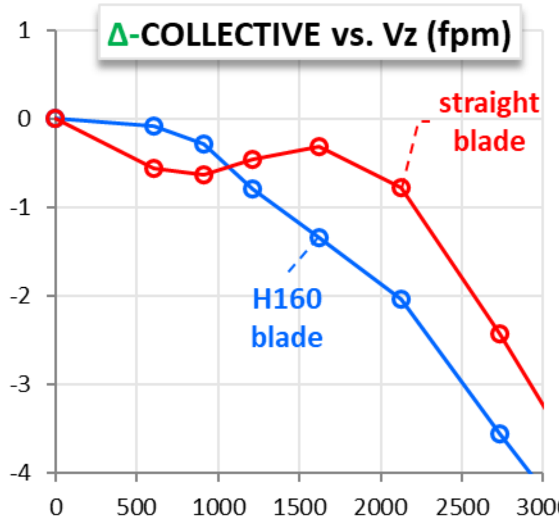


**Figure 19**: evolution of required collective pitch (expressed as Δ from hover value) with vertical rate of descent, of a H160 rotor (blue) against a generic straight blade rotor (red). The H160 rotor does not encounter any inversion of the slope, meaning continuous positive damping in the vertical axis.

It is worth mentioning that this specific behavior of the H160 double-swept blade does not only apply on average lift (and associated collective), but also on more dynamic lift fluctuations that generate the significant thrust oscillations (section 4.1). The H160 essentially actively dampens out the inflow fluctuations of VRS by constantly adapting the blade tip twist to the local load (over-twisting for more load and vice-versa). The result is lower thrust fluctuations on all rates of descent inside the VRS domain. In Figure 20 we compare again the H160 blade with a straight blade, and plot the lift fluctuations (divided by hover lift or aircraft weight) as a function of time. For these rates of descent of interest (1600 to 2700 fpm), well within VRS, we see that the H160 rotor produces less oscillations.

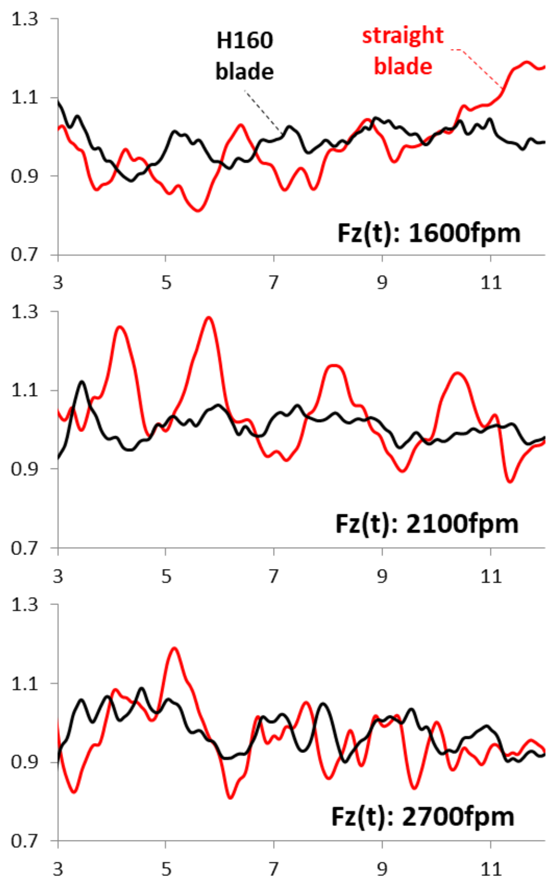


**Figure 20**: reduced lift (1 = hover lift) fluctuations as a function of time for three rates of descent inside VRS, for a H160 blade (black) and a generic straight blade (red).

## 5. CONCLUSIONS

The character of this study is a preliminary one. However, some partial conclusions can be drawn, in order to suggest directions for future studies and flight tests:

1. With relatively simple numerical methods (vortex methods – free wake) we can reproduce a sufficient portion of the physics around VRS, conduct large parametric studies, and analyze the flow characteristics in detail.
2. The intensity of the thrust oscillations due to VRS and wake interactions more in general, depends on the disc loading. VRS mappings (Vx-Vz coordinates) can be produced for various disc loadings, and thresholds can be defined. These thresholds are likely to be common for all disc loadings, when Vx and Vz are reduced by the $v_{io}$.
3. The main frequencies of thrust (and moments) oscillations inside VRS are below 3Hz, essentially between 0.5 and 1Hz (piloting frequencies), therefore interfering directly with pilot actions.
4. Entry into VRS in vertical or quasi-vertical descent causes loss of rotor damping in the vertical axis (inversion of the collective-to-Vz gradient), due to loss of average lift. This might be the main reason why pilots inadvertently enter VRS. The loss of lift occurs at the outboard part of the blade, due to the large VRS annular recirculation that reduces the local airfoils angles of attack. Airfoil stall on the inboard part of the blade is not a contributing factor on the loss of lift.
5. The behavior of the rotor when entering VRS (loss of lift and collective-to-Vz slope) depends greatly on disc loading. Thus, VRS can have a different characteristics for a light H/C than for a medium/heavy one.
6. Raising the collective when inside VRS does not worsen the situation (given sufficient power margins). It can be clearly beneficial at early stages of VRS, and its overall effectiveness depends greatly on how deep inside VRS we are.
7. The H160 rotor (double swept blades) shows much better behavior in VRS than a generic rotor with straight blades, thanks to its aero-elastic behavior. Firstly, the loss of rotor damping does not occur (at least for the examined operational DL), and secondly the thrust oscillations are milder, meaning possibly better control inside VRS.

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## 6. ACKNOWLEDGMENTS

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